Preliminary sizing and optimization of a satellite thermal control system using THERMICA.

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1 Introduction

The objective of the lab described in this report was to perform a thermal simulation on a simplified model of the SPOT satellite, a French Earth observation satellite. All spacecraft subsystems had clear and defined operational temperature ranges that needed to be fulfilled throughout the spacecraft's lifetime. The first part of the lab required to do a preliminary sizing of the thermal control system for a given spacecraft platform. The second part of the lab required us to perform a thermal simulation and optimization of the thermal control system in order to keep the subsystems in their specific temperature ranges.

2 Preliminary sizing of the thermal control system of a satellite platform.

2.1 Mission specifications

To design the thermal control system of the satellite it is necessary to identify the hottest case and the coldest case that he will encounter during its mission. There are four thermal cases :

- Winter solstice in beginning of life (BOL)
- Summer solstice in BOL
- Winter solstice in end of life (EOL)

- Summer solstice in EOL

Considering its orbit, the Earth is closer to the Sun during the winter than it is in summer. Higher temperatures will then be encountered during winter. With time, the efficiency of the radiators decreases. Consequently, the higher temperature that the satellite might reach would be in winter towards the end of its life. Therefore, the coldest case is the summer solstice in BOL and the hottest one is the winter solstice in EOL.

The main constraint to size the thermal system was to make sure that the temperature of each face in which a piece of equipment is installed stays in the range between -10°and 40°. However, in order to have some margin, for the calculations it was considered a stricter range between 0°and 20°.

2.2 Calculation of the radiators areas and heaters power

2.2.1 Calculation of absorbed fluxes.

The thermal fluxes absorbed by each face of the satellite have been calculated for one orbit around the Earth with Thermica.

These results confirm the previous hypothesis. According to tables 1, 2, 3 and 4 the thermal cases are from the hottest to the coldest: Winter solstice in EOL, Summer solstice in EOL, Winter solstice in BOL, and Summer solstice in BOL.

A difference can be noticed between EOL and BOL. The thermal flux absorbed is higher in EOL which highlights the fact that in the end of their life, the radiators are less efficient and more heat is absorbed by the satellite.

The absorbed flux of each surface M_a can be calculated with equation 1

$$\boxed{M_a = M_{sun} + M_{EAlbedo} + M_{EIR}} \tag{1}$$

where M_{sun} is the absorbed flux due to the sun thermal flux, $M_{EAlbedo}$ due to the Earth albedo and M_{EIR} due to the Earth IR.

These three absorbed fluxes have been calculated on Thermica and are shown in tables 1, 2, 3 and 4.

Table 1: Absorbed flux in summer BOL (W/m^2).

Face	M_{sun}	$M_{MAlbedo}$	M_{MIR}	M_a
+X	38,67555	4,796102	35,96345	79,435102
-X	0	4,20335	35,96345	40,1668
+Y	44,96844	4,53068	35,96345	85,46257
-Y	44,98325	4,524921	35,96345	85,471621
+Z	60,55969	0	0	60,55969
-Z	7,905001	16,50265	131,1402	155,547851

Table 2: Absorbed flux in winter BOL (W/m^2).

Face	M_{sun}	$M_{MAlbedo}$	M_{MIR}	M_a
+X	57,15578	5,040743	35,96345	98,159973
-X	0	4,175123	35,96345	40,138573
+Y	46,78883	4,630494	35,96345	87,382774
-Y	46,78354	4,628605	35,96345	87,375595
+Z	62,17968	0	0	62,17968
-Z	9,116266	16,89037	131,1402	157,146836

2.2.2 Calculation of radiators rejection capacities.

For the hottest and coldest cases (respectively 20°and 0°), assuming that the radiators can be considered as gray bodies the emitted flux of a surface can be calculated with equation 2.

$$\boxed{M_e = \varepsilon * \sigma * T^4} \tag{2}$$

Table 3: Absorbed flux in summer EOL (W/m^2).

Face	M_{sun}	$M_{MAlbedo}$	M_{MIR}	M_a
+X	48,98903	6,075139	35,96345	91,027619
-X	0	5,324243	35,96345	41,287693
+Y	56,96003	5,738861	35,96345	98,662341
-Y	56,97878	5,731067	35,96345	98,673297
+Z	76,70894	0	0	76,70894
-Z	10,013	20,90336	131,1402	162,05656

Table 4: Absorbed flux in winter EOL (W/m^2).

Face	M_{sun}	$M_{MAlbedo}$	M_{MIR}	M_a
+X	72,39732	6,384941	35,96345	114,745711
-X	0	5,288489	35,96345	41,251939
+Y	59,26585	5,865293	35,96345	101,094593
-Y	59,25916	5,862899	35,96345	101,085509
+Z	78,76093	0	0	78,76093
-Z	11,54727	21,39447	131,1402	164,08194

where T is the temperature of the radiator in kelvin and σ is the Stefan Boltzmann's constant. In the end, the net thermal flux per unit surface is given by equation 3.

$$\boxed{M = M_e - M_a} \tag{3}$$

The calculations give the results in table 5.

Table 5: Net thermal flux per unit surface (W/m^2).

Face	+X	-X	+Y	-Y	+Z	-Z
Summer BOL (W/m^2)	166,2213922	205,4896942	160,1939242	160,1848732	185,0968042	90,10864324
Winter EOL (W/m^2)	211,2021557	284,6959277	224,8532737	224,8623577	247,1869367	161,8659267

2.2.3 Placement of the equipment.

The equipment should be positioned according to the power they dissipate. The most efficient combination, is to place the equipment which dissipate the most power on the face with the higher rejection capacity. Considering the hottest and coldest cases, the cases from the highest to the lowest rejection capacities are:

- $+Z$
- $-Y$
- $+Y$
- $-Z$

$+X$ and $-X$ faces are not included considering that they are not supposed to support any equipment. The rejection capacities of Y faces are quite close and their order in the previous list could then be switched.

Equipment	**Nominal mode dissipated power [W]**	**Survival mode dissipated power [W]**
Power supply	150	20
AOCS	110	30
Telemetry	70	0
On-board data processing	15	10

Table 6: Dissipated power from the different spacecraft subsystems.

The equipment is supposed to be operating in nominal mode and according to the values for their power dissipation in Table 6, it should be positioned as following:

- $+Z$: Power supply
- $+Y$: AOCS
- $-Y$: Telemetry
- $-Z$: On-board data processing

It is also necessary to consider the survival mode. In this case $+Z$ points toward the Sun and the satellite is spinning around the Z axis. $+Z$ will then have the higher absorbed flux and should be associated with the equipment dissipating the lower power in survival mode, which would be the telemetry. Considering this new parameter, the final positioning of the equipment should be:

- $+Z$: Telemetry
- $+Y$: Power supply
- $-Y$: AOCS
- $-Z$: On-board data processing

2.2.4 Areas of the radiators.

Assuming that the radiators temperature should remain below $20°C$, the area of the radiators can be determined by writing the thermal equilibrium as in equation 4.

$$\boxed{P_e = P_a + P_d} \tag{4}$$

where P_e is the emitted power, P_a absorbed and P_d dissipated. Writing these power with area and flux, the area can finally be calculated with equation 5.

$$\boxed{A = \frac{P_d}{\epsilon * \sigma * T^4 - M_a}} \tag{5}$$

With $T = 20°C$ and using the values of the hot case (winter EOL) of table 4 for the absorbed flux and of the operating nominal mode for the dissipated power, the radiators should have the areas written in table 7.

Table 7: Minimum areas for the radiators in order to keep the temperature below $20°C$.

Face	+Y	-Y	+Z	-Z
Radiator area (m^2)	0.67	0.49	0.28	$9.3 * 10^{-2}$

2.2.5 Power of the heaters.

In order to keep the temperature upon $0°C$, heaters can be placed on each face. To determine the amount of power that they should dissipate, equation 4 can be used again and gives equation 6.

$$\boxed{M_H = A * \epsilon * \sigma * T^4 - A * M_a - P_d} \tag{6}$$

where M_H is the power of the heater, A the area of the radiator.

With $T = 0°C$ in the cold case (summer BOL) and considering that the equipment are in the standby nominal mode, the heaters should have the power written in table 8.

Table 8: Minimum power for the heaters in order to keep the temperature upon $0°C$.

Face	+Y	-Y	+Z	-Z
Heater power (W)	57	28	52	-1.6*

*This heater minimum power is negative which means that it is not needed.

3 Thermal simulation and optimization of the thermal control system

3.1 Nodal diagram of the thermal components

The components of the satellite are transferring energy with each other in different ways. The components that are mounted together mechanically will exchange heat by conduction. The components that are not directly contacted with each other can exchange heat by radiation. To clarify these power exchange method a nodal diagram of the thermal components are made and showed below. In the graph, the conductivity between each pair of components is also showed.

According to the structure of the Spot, the following mechanical connections exist. Each equipment is mounted directly on the corresponding radiator and then the radiator is mounted on the corresponding wall. The MLIs are mounted mechanically on the walls as well. But there are no mechanical contact between the different faces. So beside conductivity, the walls are exchange energy with internal radiation.

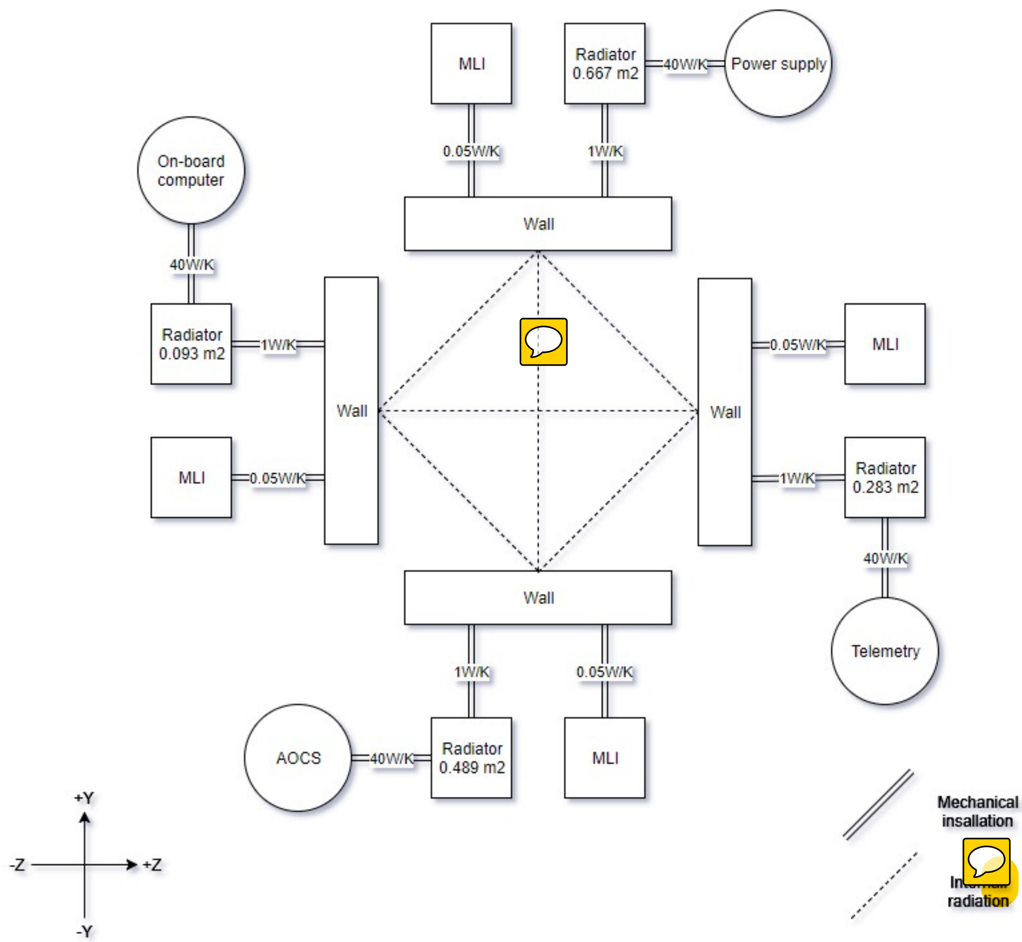

Figure 1: Nodal diagram

3.2 Temperature calculation.

There are three choices of the conductive coupling between the equipment and the radiator: connected with the thermal joint with conductivity $40W/K$ or let equipment directly screwed into the radiator which corresponds to the conductivity $10W/K$ or insulate the equipment from the radiator using washers which shall give the conductivity $6 * 0.1W/K = 0.6W/K$. Since the radiators are used to reduce the temperature of the equipment, it is desirable the heat transferring to be efficient. So the thermal joint which has the highest conductivity is chosen to be the connection between the equipment and the radiators.

Figures 2, 3, 4, and 5 show the temperatures on the different faces of the satellite for the hot case without internal radiation.

From those figures it is evident that the temperature requirement is largely respected.

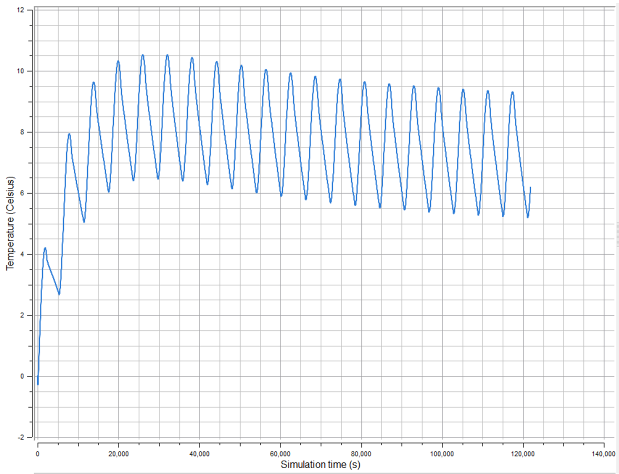

Figure 2: Satellite +Z face temperature in hot case without internal radiation.

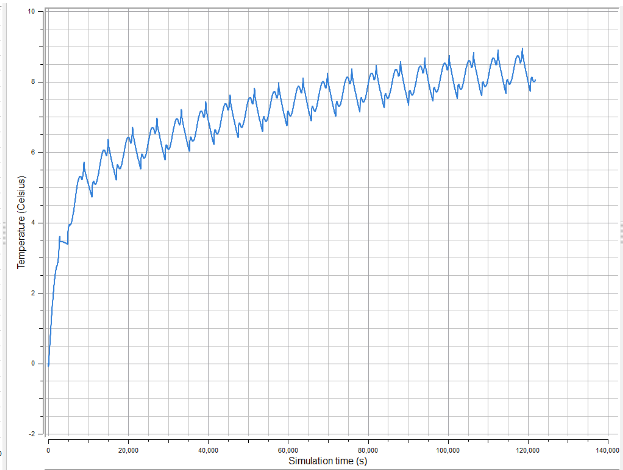

Figure 3: Satellite -Z face temperature in hot case without internal radiation.

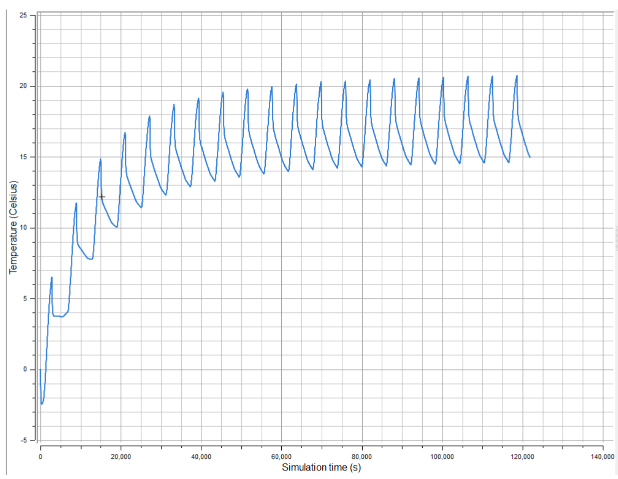

Figure 4: Satellite +Y face temperature in hot case without internal radiation.

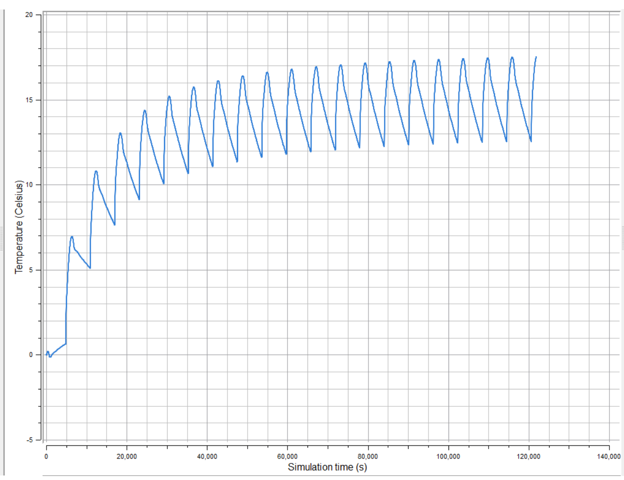

Figure 5: Satellite -Y face temperature in hot case without internal radiation.

Figures 6, 7, 8, and 9 show the temperatures on the different faces of the satellite for the hot case with internal radiation.

The main difference from the previous case is that while without internal radiation there is a larger gap between the temperature of the different faces (in particular faces +Y and -Y are the hottest), by taking into account internal radiation this gap is reduced and the temperature is more uniform.

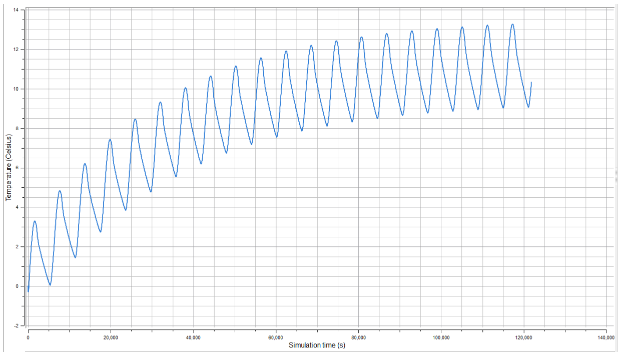

Figure 6: Satellite +Z face temperature in hot case with internal radiation.

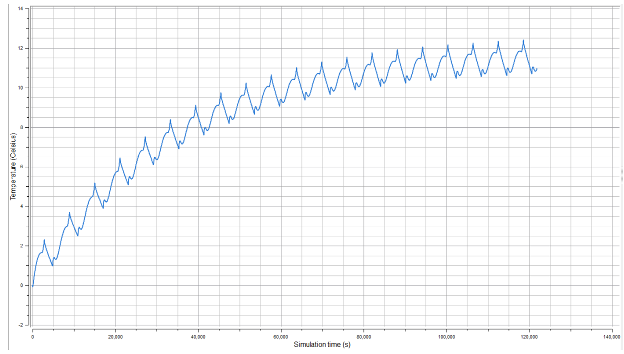

Figure 7: Satellite -Z face temperature in hot case with internal radiation.

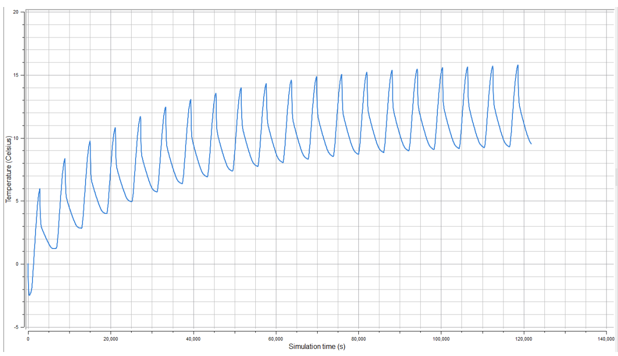

Figure 8: Satellite +Y face temperature in hot case with internal radiation.

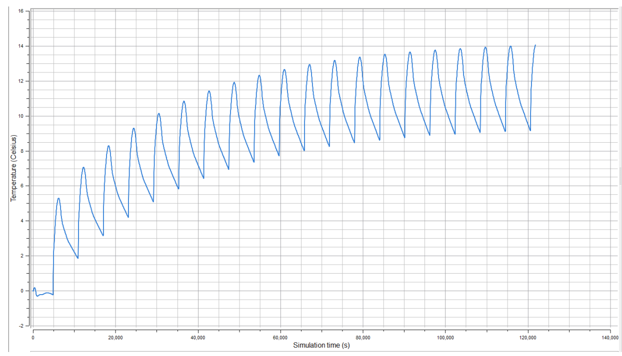

Figure 9: Satellite -Y face temperature in hot case with internal radiation.

Figures 10, 11, 12, and 13 show the temperatures on the different faces of the satellite for the cold case with internal radiation.

In this case the temperatures go below 0° even if that was the limit used to size the heaters. Indeed they stay at the actual limit of -10°. This behavior can be explained by noticing that in the user script used to perform the thermal simulation, the heaters controller was set to activate the heaters when the temperature had reached -10° and to turn them off when it had went back to -5°.

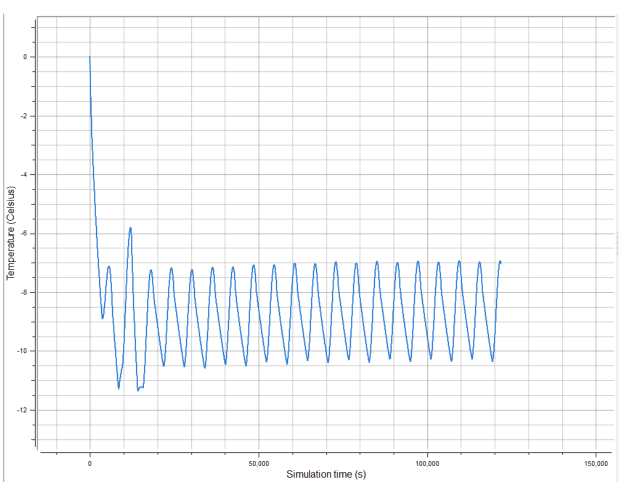

Figure 10: Satellite +Z face temperature in cold case with internal radiation.

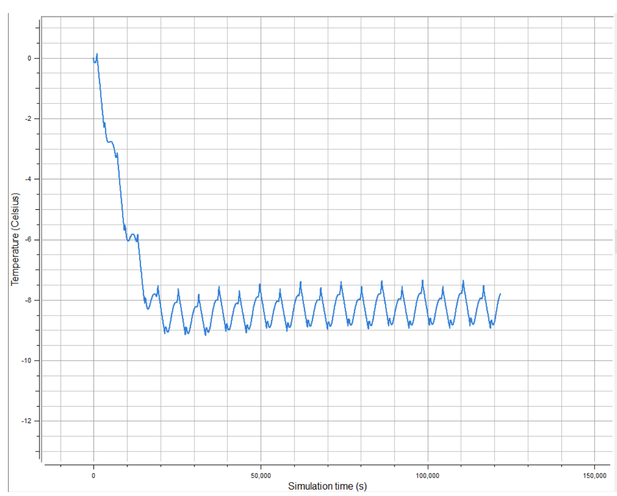

Figure 11: Satellite -Z face temperature in cold case with internal radiation.

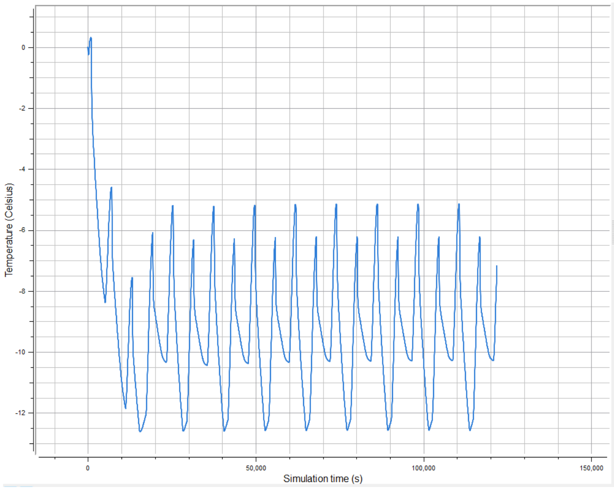

Figure 12: Satellite +Y face temperature in cold case with internal radiation.

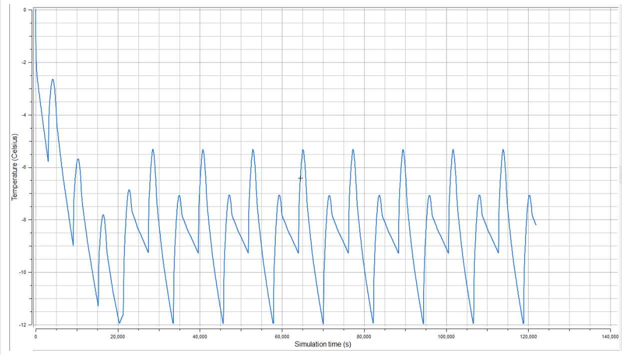

Figure 13: Satellite -Y face temperature in cold case with internal radiation.

Figures 14, 15, 16, and 17 show the heater powers on the different faces of the satellite for the cold case with internal radiation.

The heater powers profile with time match the temperature profile. For example, the temperature of face +Z never reaches -5°, therefore, the heater on that side never turns off.

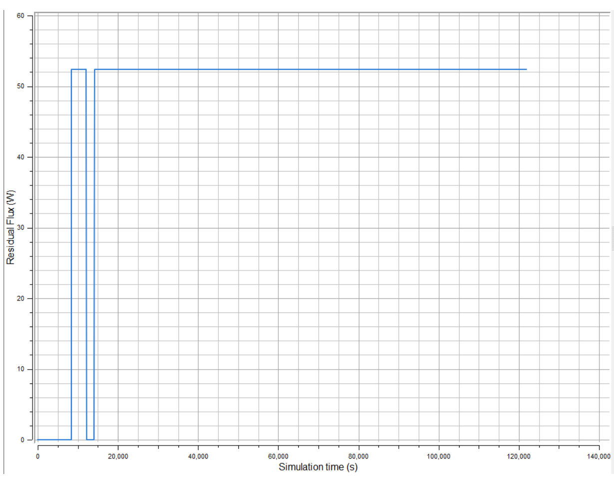

Figure 14: Satellite +Z face heater power in cold case with internal radiation.

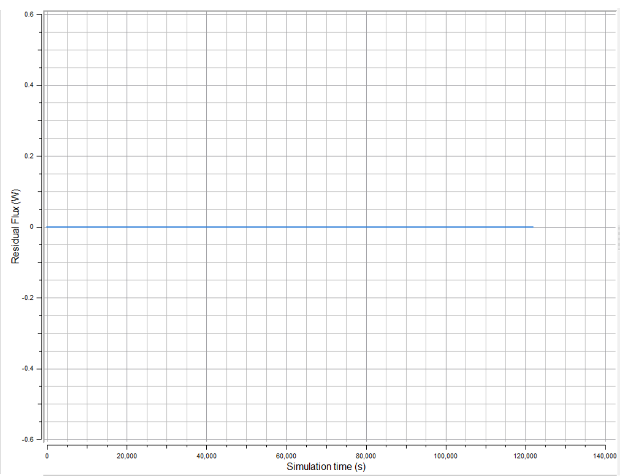

Figure 15: Satellite -Z face heater power in cold case with internal radiation.

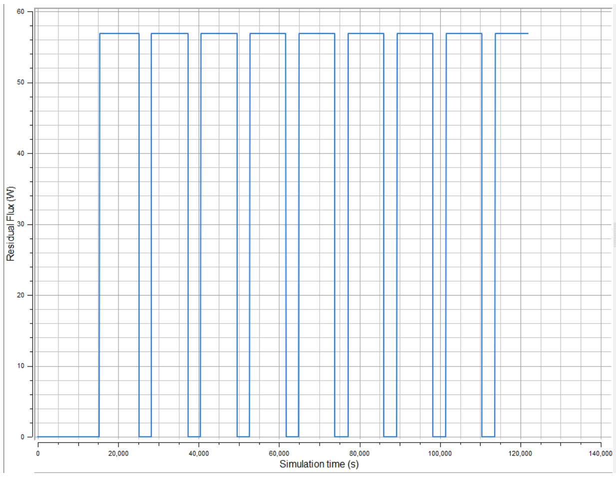

Figure 16: Satellite +Y face heater power in cold case with internal radiation.

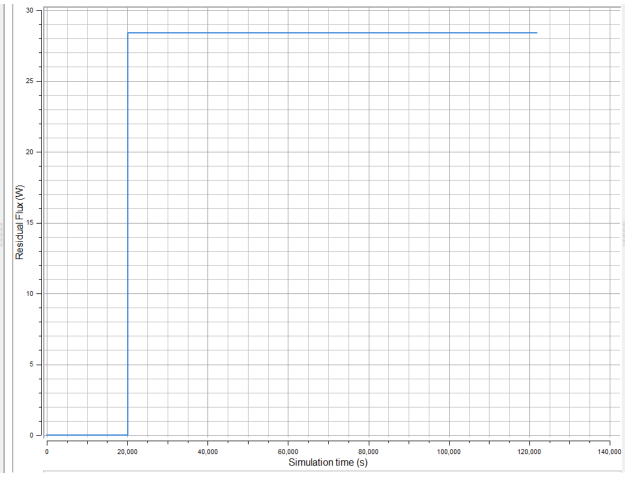

Figure 17: Satellite -Y face heater power in cold case with internal radiation.

It can be observed from the graphs that the heaters are often on. In other word, the duty cycles of the heaters are too large, which is called saturation. It is desired not to have too high duty cycles in order to have margin in case more heating power is needed. At the same time having a too small duty cycle means that the heaters are oversized, therefore, the best trade-off is considered to be between 60% and 70%. To reduce the duty cycle, the power of the heaters need to be increased.

Different value of the heaters are tested and the corresponding duty cycles are calculated by simulation. This iteration gives the following result with duty cycle between 60% and 70%.

Table 9: The power of heaters which optimize the duty cycles of the heaters

Face	+Y	-Y	+Z	-Z
Heater power (W)	65	40	100	0

Figures 18, 19, 20, and 21 show the optimized heater powers on the different faces of the satellite.

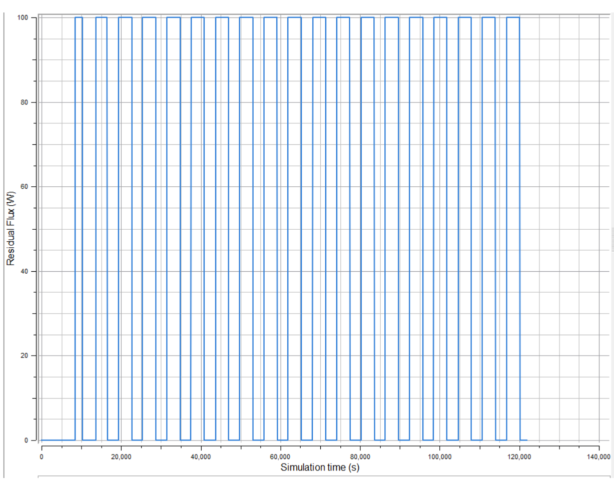

Figure 18: Satellite +Z face optimized heater power in cold case with internal radiation.

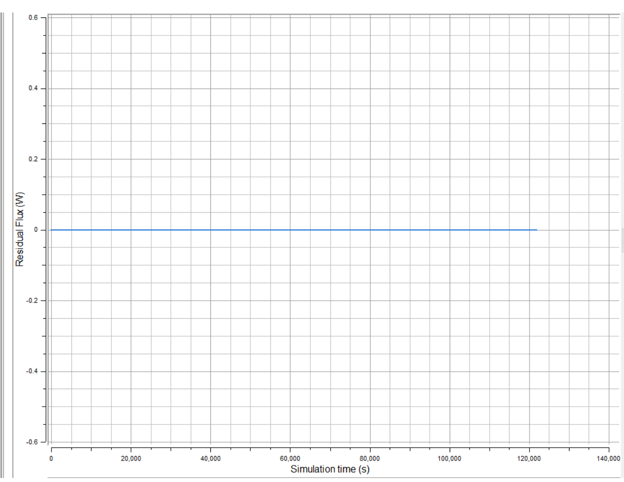

Figure 19: Satellite -Z face optimized heater power in cold case with internal radiation.

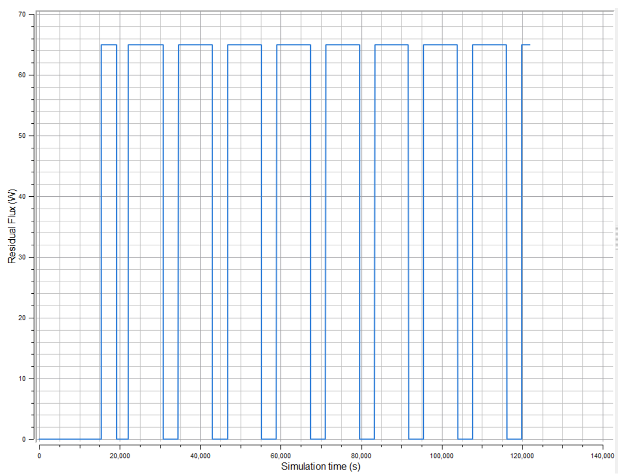

Figure 20: Satellite +Y face optimized heater power in cold case with internal radiation.

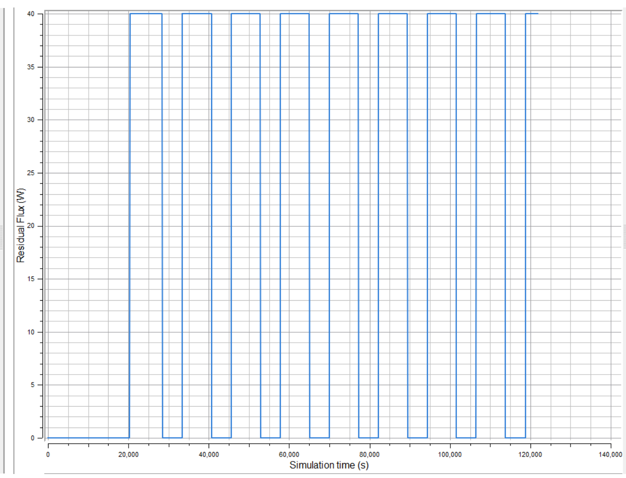

Figure 21: Satellite -Y face optimized heater power in cold case with internal radiation.

4 Conclusion

This laboratory work showed how a thermal regulation system can be sized by means of a combination of simple mathematical equations representing the heat exchange between the spacecraft and the outer space and a powerful software for thermal simulation. The equations were used to find reasonable values for the size of the radiators and the heater power, using as input the heat fluxes obtained by the software SYSTEMA, but this results had to be validated through the software itself. The different simulations showed the evolution of temperatures and heat from the heaters during the mission. By looking at the obtained data and using an iterative process it was eventually possible to further optimize the sizing of the heaters in order to have a safe margin in case more heating power will be needed and to not have them excessively oversized.

5 Division of work

- J. Imbert: Worked on the calculations of radiators areas and heaters. Redaction of the part "Preliminary sizing of the thermal control of a satellite platform".
- Y. Jiao: Worked on the simulation setup and nodal model. Redaction of the part nodal diagram and thermal components.
- F. Raiti: Simulation setup; mathematical model for thermal system sizing; redaction of the subsections "Temperature calculation" and "Conclusion".
- C. Muresan: